NASA TECHNICAL NOTE

NASA TN D-2662

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1965

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SUMMARY

Cavitation of liquid Freon-114 (dichlorotetrafluoroethane) was induced on the walls of a Venturi in a closed-return hydrodynamic tunnel. The Venturi used a quarter round to provide the transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat section. At a fixed velocity, the incipient-cavitation parameter decreased as much as 30 percent when the liquid temperature was increased from 0° to 80° F. (The incipient-cavitation parameter is the ratio of the difference between an upstream reference pressure at incipient cavitation and the vapor pressure to the velocity pressure of the upstream flow.) At a fixed temperature, the parameter increased as much as 50 percent when the approach velocity was increased from 20 to 47 feet per second. Values of the incipient-cavitation parameter indicated local effective tensions within the liquid that ranged from 4 to 20 feet of liquid, depending on temperature and velocity.

INTRODUCTION

Cavitation may be described as the formation and subsequent collapse of vapor cavities in a flowing liquid brought about by pressure changes resulting from changes in flow velocity. In visible systems, incipient cavitation usually denotes the first small but visible rupture (bubble) in the liquid. Generally, at or just prior to incipient cavitation, the liquid is locally at a pressure less than the vapor pressure corresponding to the liquid temperature (refs. 1 to 4). Thus, the liquid is superheated locally or is effectively in tension. Experimental studies have shown that the amount of tension at incipient cavitation is different for water than for nitrogen flowing in the same tunnel and Venturi test section (refs. 1 and 2). Although the existence, source, size, and exact role of nuclei in the cavitation process are not clearly understood (ref. 3), the effect of pure fluid properties alone seems to be intimately involved in the cavitation process. At present, the role of any particular fluid property is insufficiently known, and a better understanding of property effects is required to improve design of hydraulic equipment (ref. 5).

The purposes of this investigation were to determine the incipient-cavitation characteristics of Freon-114 (dichlorotetrafluoroethane) flowing in the same tunnel and Venturi as used previously for water and nitrogen (refs. 1 and 2) and thus to extend the range of fluid properties investigated. The study was conducted at the NASA Lewis Research Center as part of a general program of cavitation research. Cavitation was induced on the walls of a transparent Venturi test section in a closed-return tunnel, which, for temperature control, was submerged in a bath of antifreeze solution. The Venturi uses a quarter round (nominal radius, 0.183 in.) to provide the transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat section. The flow velocity in the Venturi approach section was varied from 20 to 47 feet per second, and the liquid temperature was varied between 0° and 80° F. The ranges of velocity and temperature were determined by facility limitations.

APPARATUS

Aside from the minor additions noted herein, the facility used in the present study is the same as that described in detail in references 1 and 2. Briefly, the facility consists of a small closed-return hydrodynamic tunnel (capacity, approx 10 U.S. gal) designed to circulate (by means of a 700 gal/min centrifugal pump) various liquids, including cryogenic liquids. The tunnel accommodates 12-inch-long test sections having maximum inlet diameters of 1.743 inches. A liquid bath (capacity, approx 80 U.S. gal) surrounds the tunnel to serve as a heat sink and also to control tunnel liquid temperature. For temperature control, a slowly circulated bath mixture of 60 percent ethylene glycol and water was provided. This mixture exchanged heat with a sump-mounted, single-tube coil carrying either low-pressure steam or cold nitrogen gas (an addition to the facility of ref. 1). Absolute values of tunnel liquid temperature were measured with a calibrated copper-constantan thermocouple (accuracy, $\pm 0.5^{\circ}$ F) mounted on the flow centerline 14.5 inches upstream of the test section. Liquid pressure level in the tunnel was varied by gas pressurization of the ullage space above a butyl rubber diaphram (an addition to the facility of ref. 1) in the expansion chamber. Pressures within the tunnel and test section were measured by mercury manometers or by calibrated bleed-type precision gages (accuracy, ± 0.15 lb/sq in.).

The transparent-plastic Venturi test section used with Freon-114 was the same one as used in previous cavitation studies of water and nitrogen (refs. 1 and 2). The Venturi (fig. 1) uses a slightly modified quarter round (nominal radius, 0.183 in.) to provide the transition from a 1.743-inch-diameter approach section to a 1.377-inch-diameter throat

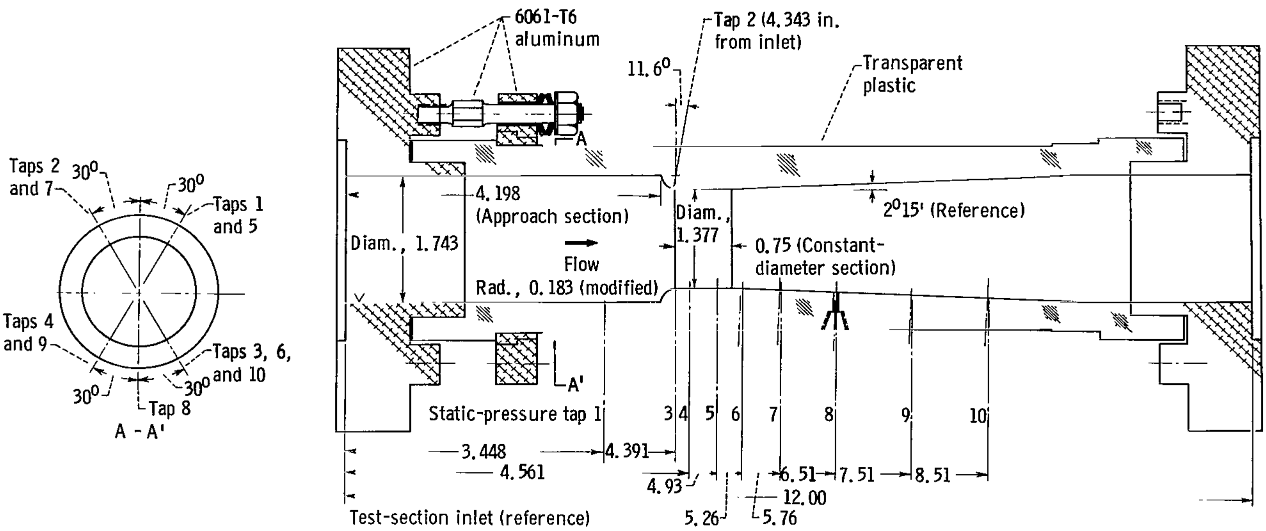


Figure 1. - Sketch of hydrodynamic Venturi section showing dimensions and pressure instrumentation. (Dimensions in inches.)

section. The 0.75-inch-long, constant-diameter throat is followed by a conical diffuser. The precise contour of the modified quarter-round region is given in reference 1.

The first appearance of vapor cavities was photographed by a 4- by 5-inch still camera in conjunction with a 0.5-microsecond, high-intensity flash unit.

PROCEDURE

Test Liquid

A commercial grade of Freon-114 (dichlorotetrafluoroethane) was used as the test liquid. It is a clear, colorless liquid with a normal boiling point of 38.8° F. Some liquid Freon-114 properties (refs. 6 to 8) are presented for convenience in table I.

An evacuated and subcooled tunnel was twice charged with Freon-114. One charge was direct from the cylinder as received from the manufacturer, who specifies a maximum noncondensable gas content (assumed to be air) of 1.5 percent by volume in the vapor phase. This is equivalent to an air content of 20 parts per million (mg air/kg liquid). Because the original contents of another Freon-114 cylinder had been inadvertently pressurized with nitrogen gas, this liquid was reprocessed to remove or reduce the gas content before it was used in the tunnel. The liquid was reprocessed by being heated to 110° F in a closed tank; then, with heat off, the tank was vented to the atmosphere until about 5 percent by weight was boiled off. The gas content of this reprocessed charge is unknown. The solubility coefficient for air in Freon-114 is much higher than that for air in water and, like that for water, increases with decreasing temperature. For instance,

TABLE I. - PROPERTIES OF LIQUID FREON-114

Temperature, ^{o}F	Vapor pressure, ft of Freon-114 (a)	Specific weight, lb/cu ft (a)	Absolute viscosity, (lb-sec)/sq ft (b)	Surface tension, lb/ft (c)
-10	6.63	99.42	13.7×10^{-6}	12.32×10^{-4}
0	8.70	98.50	12.5	11.85
10	11.27	97.57	11.55	11.37
20	14.43	96.63	10.77	10.90
30	18.29	95.67	10.09	10.41
40	22.93	94.69	9.48	9.93
50	28.48	93.70	8.94	9.46
60	35.07	92.69	8.45	9.00
70	42.83	91.65	8.03	8.53
80	51.91	90.59	7.67	8.10
90	62.47	89.51	7.30	7.64

[a]Ref. 6.
[b]Ref. 7.
[c]Ref. 8.

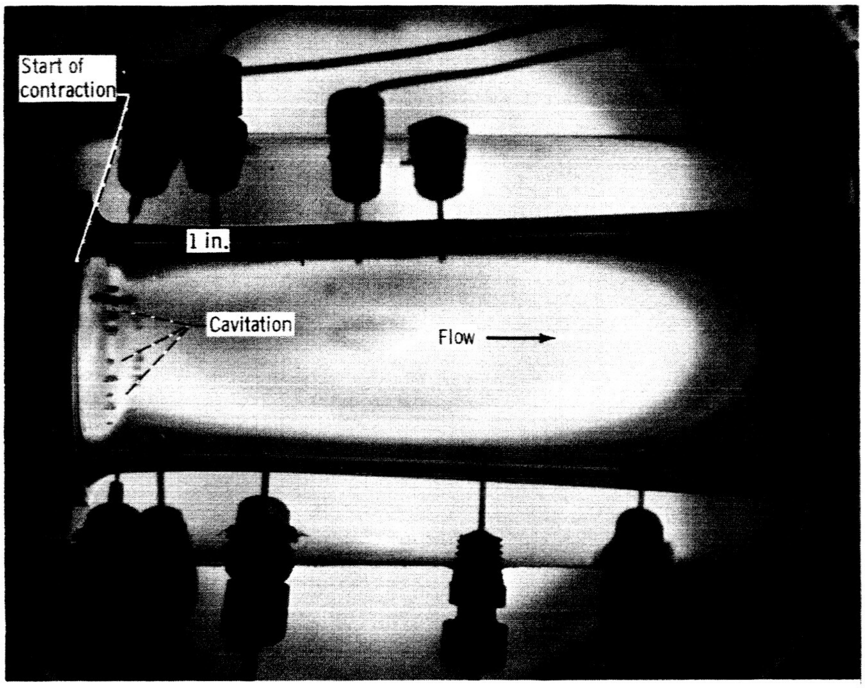
at a total pressure (air plus vapor) of 1 atmosphere, the manufacturer indicates that air-saturated Freon-114 contains about 140 parts per million at a temperature of 32^{o} F, and about 1000 parts per million at 0^{o} F.

Criteria and Appearance of Incipient Cavitation

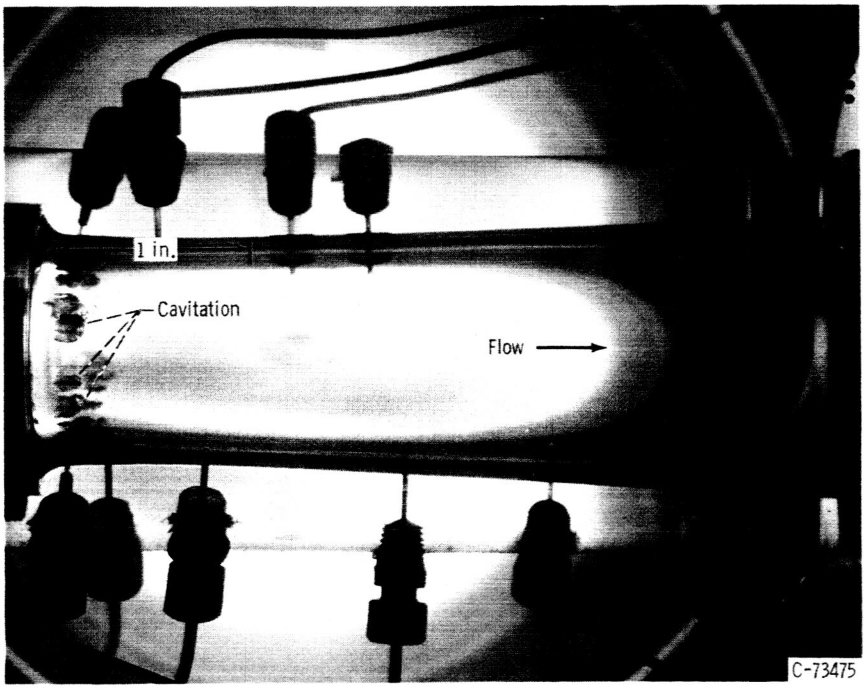
Cavitation was induced on the walls of a Venturi and controlled by varying the overall liquid pressure level in the tunnel while maintaining a fixed approach velocity and a constant temperature (within $\pm0.5^{o}$ F). The operating condition at which the formation and collapse of vapor bubbles near the Venturi surface is just detectable by eye is defined herein as incipient cavitation. At this condition, free-stream values of static pressure h_0, velocity V_0, and temperature (for vapor pressure h_v) were measured for subsequent determination of the incipient cavitation parameter K_i. (Symbols are defined in the appendix.) All free-stream values refer to an axial location in the approach section that is about 3/4 inch upstream of the start of the quarter round (i.e., at tap 1, fig. 1). Typical photographs of incipient cavitation of Freon-114 are shown in figure 2. In general, incipient cavitation at all conditions studied was evidenced by intermittent (approx 5/sec) bursts of vapor cavities (minimum length, 1/8 in.) with leading edges located in the region of minimum pressure on the quarter round. These bursts occurred in a random manner about the periphery of the Venturi, each burst lasting but a few milliseconds. Incipient-cavity size generally decreased, and frequency of occurrence increased with increasing speed. Increased temperature appears to increase the size of the incipient cavity of Freon-114, as shown in figure 2. There were no hysteresis effects; that is, no measurable differences in incipient conditions were observed whether the incipient state was approached from initially noncavitating flow by decreasing pressure, or from an initially cavitated state by increasing pressure.

Noncavitating Pressure Distribution

The noncavitating wall pressure distribution in the critical low-pressure region of the



(a) Free-stream temperature, -1.3° F; free-stream velocity, 25.9 feet per second; incipient-cavitation parameter, 2.80.



(b) Free-stream temperature, 60.7° F; free-stream velocity, 26.8 feet per second; incipient-cavitation parameter, 2.40.

Figure 2. - Appearance of incipient cavitation of Freon-114 at two free-stream temperatures.

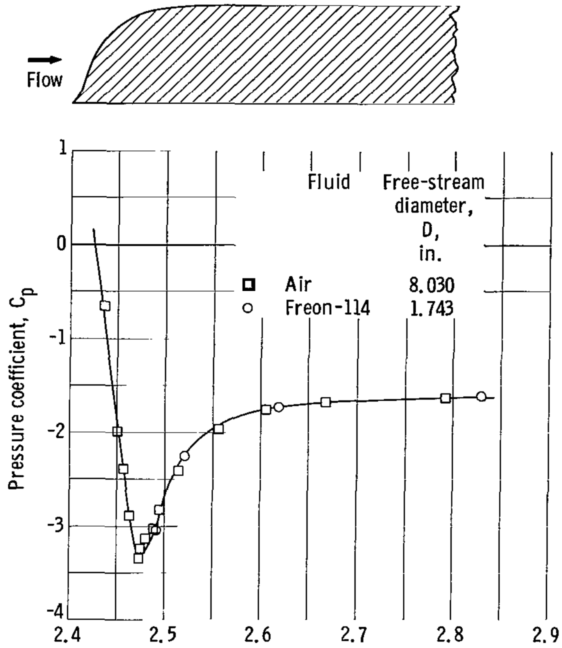


Figure 3. - Noncavitating pressure distribution for Freon-114 Venturi and aerodynamic Venturi.

Venturi is used in evaluating cavitation data. This pressure distribution is obtained primarily from previous aerodynamic studies (refs. 1 and 2) and is presented in figure 3. The aerodynamic data are from the accurately scaled wind tunnel model of the Venturi with free-stream diameter of 8.030 inches described in reference 2. The air data are slightly different from those previously reported in that an improved method is now used to correct for compressibility. The locally measured air pressures obtained at numerous levels of free-stream Mach number are extrapolated to a Mach number of zero (the incompressible case). Previously (refs. 1 and 2), compressibility factors obtained from oversimplified corrections to the incompressible pitot equation were used. Figure 3 shows good agreement between pressure coefficients for air and the Freon-114 studied herein. A study of available hydrodynamic pressure data in the same Venturi indicates a critical Reynolds number (based on the approach-section diameter of 1.743 in., the free-stream velocity, and the liquid properties) near 0.4×10^6, above which all local pressure coefficients remain constant. The minimum Reynolds number for the Freon-114 data herein is about 0.7×10^6. Thus, figure 3 represents the unchanging pressure distribution for Freon-114, and in particular, a value of $C_{p,min}$ of -3.35 at an x/D location of 2.471. This constant value of -3.35 for $C_{p,min}$ at all Reynolds numbers above 0.4×10^6 differs slightly from that previously reported in references 1 and 2 (wherein $C_{p,min}$ varied from -3.28 to -3.62 as Reynolds numbers increased from 0.4×10^6 to 4×10^6) because of the improved compressibility correction described herein. The new $C_{p,min}$ value of -3.35 should replace all $C_{p,min}$ values of references 1 and 2; this results in only small changes in the tension values and in no change in the values of the incipient-cavitation parameter K_i.

RESULTS AND DISCUSSION

The conventional incipient-cavitation parameter K_i is the ratio of the difference between a free-stream reference pressure at incipient cavitation h_0 and the vapor pressure h_v to the velocity pressure or head of the free-stream flow $V_0^2/2g$. The

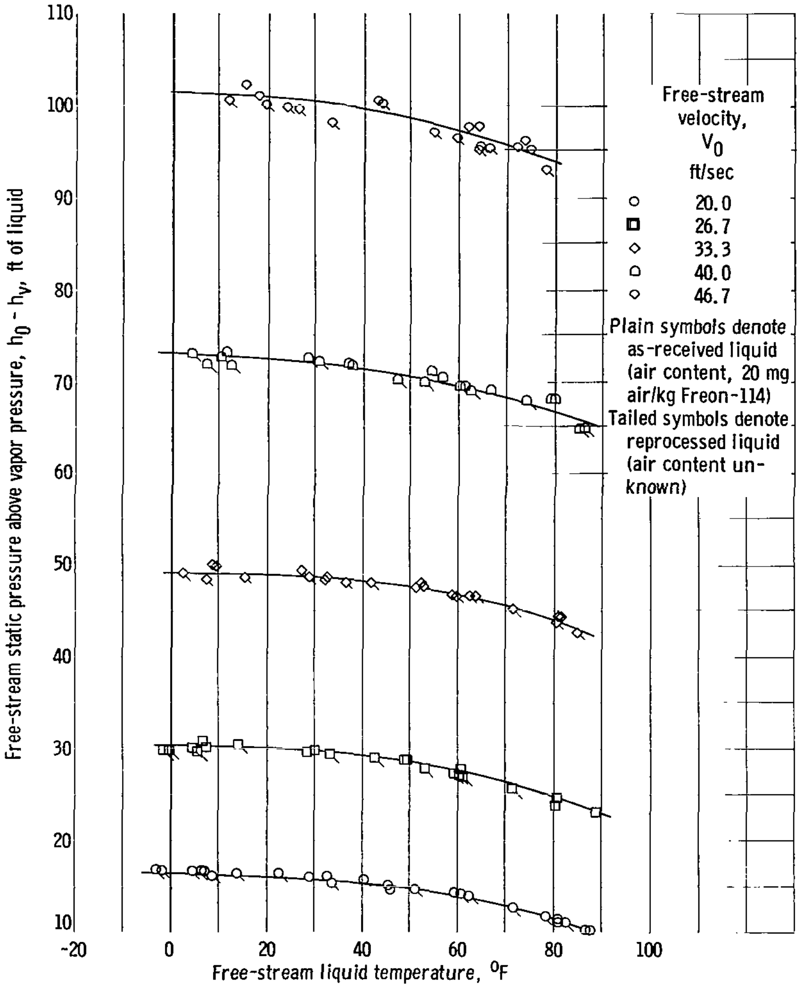


Figure 4. - Free-stream static pressure above vapor pressure at incipient cavitation as function of free-stream liquid temperature for several free-stream velocities.

basic data are given in figure 4, where the numerator of K_i, $h_0 - h_v$, is shown as a function of liquid temperature for the five free-stream velocities and the two loadings of liquid. Free-stream static pressure above vapor pressure at incipient cavitation $h_0 - h_v$ increases with increasing velocity and decreases with increasing temperature. The reprocessed liquid with unknown gas content yields the same results as the as-received liquid with an air content of 20 parts per million. The data of figure 4 are well represented by the faired lines drawn for each velocity, and the values on these lines are used to calculate K_i at constant temperature over the range of free-stream velocities tested. Thus, K_i as a function of free-stream velocity for liquid temperatures of 0°, 40°, and 80° F is given in figure 5. The negative noncavitating minimum-pressure coefficient $-C_{p,min}$ is also shown for reference. The incipient-cavitation parameter K_i increases with increasing velocity, the curves tending to parallel the $-C_{p,min}$ value at the higher

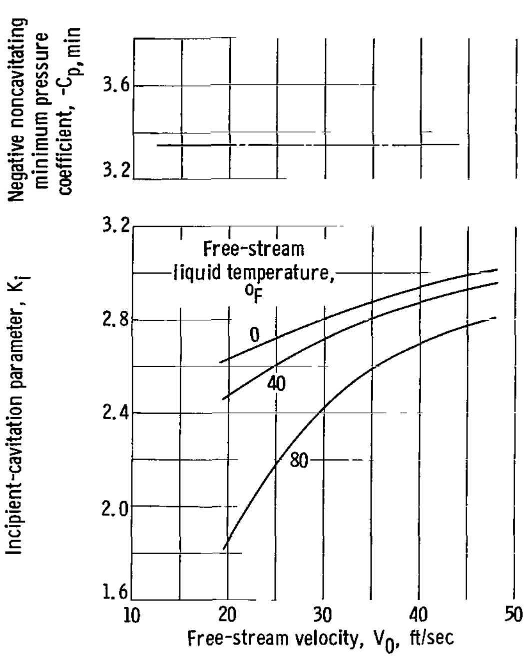


Figure 5. - Incipient-cavitation parameter (from data fairing of fig. 4) for Freon-114 and negative noncavitating minimum pressure coefficient as functions of free-stream velocity and liquid temperature.

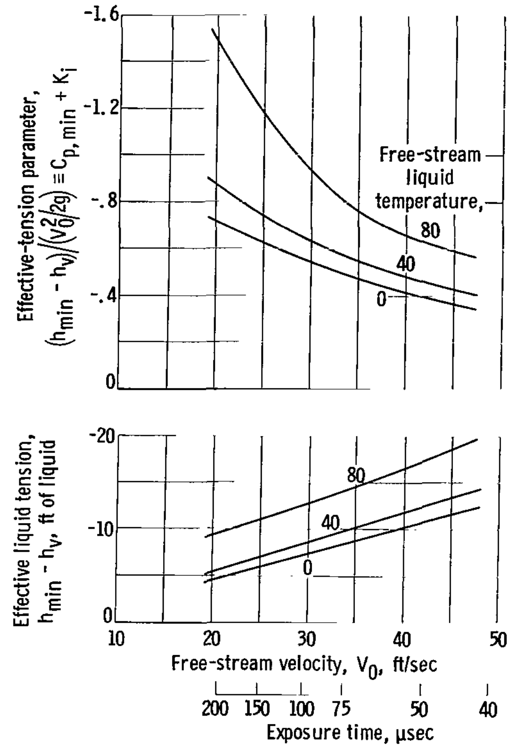


Figure 6. - Effective liquid tension and effective-tension parameter (from data fairing of fig. 4) for Freon-114 based on incipient cavitation. Exposure time scale for 40° F data only.

velocities. The velocity effect on K_i is greatest at the highest temperature (80° F), K_i increasing about 50 percent as velocity increases from 20 to 47 feet per second. As previously indicated, K_i decreases with increasing temperature, and figure 5 shows the greatest effect at the lowest velocity. At a value of V_0 of 20 feet per second, K_i decreases about 30 percent with an increase in liquid temperature from 0° to 80° F.

The Freon-114 values of K_i are always less than $-C_{p,\,min}$, which indicates that at incipient cavitation the minimum pressure on the Venturi surface h_{min} is always less than the free-stream vapor pressure h_v. With $h_{min} < h_v$, effective liquid tension $h_{min} - h_v$ is said to exist within the liquid (ref. 1). The difference between $-C_{p,\,min}$ and K_i is the ratio of effective liquid tension to velocity head $V_0^2/2g$. For convenience, the negative of this difference or $C_{p,\,min} + K_i$ is called the effective tension parameter, which, along with values of effective liquid tension, is shown in figure 6. The tension parameter for Freon-114 decreased continuously with increased velocity for all temperatures and increased with temperature at all velocities. At 80° F, the value of effective liquid tension ranged from about 9 to 20 feet of Freon-114 at free-stream velocities of 20 to 47 feet per second, respectively. At 0° F these values of effective liquid tension were nearly halved.

The tension values of figure 6 were the maximum values experienced by the liquid at or just prior to incipient cavitation because they were determined by comparing K_i with the minimum-pressure coefficient $C_{p,min}$. However, as the fluid flowed through the pressure profile of figure 3, it experienced, just prior to incipient conditions, a range of tensions or pressure decrements relative to vapor pressure that varied from zero when K_i and $-C_p$ were first equal, to the maximum values of figure 6 and then back to zero again.

The total time the fluid is below the vapor pressure is called the exposure time (ref. 2). Exposure times for the 40° F data only are indicated at the bottom of figure 6 for reference. For example, at 40° F exposure time decreased from about 200 to 50 microseconds for a velocity increase from 20 to 40 feet per second.

SUMMARY OF RESULTS

Experimental studies of incipient cavitation induced on the walls of a Venturi (quarter-round transition section) in a small closed-return tunnel using liquid Freon-114 (dichlorotetrafluoroethane) over a range of temperatures and velocities yielded the following principal results:

1. At a fixed velocity, the incipient-cavitation parameter K_i decreased as much as 30 percent when the liquid temperature was increased from 0° to 80° F, and at a fixed temperature, K_i increased as much as 50 percent when the free-stream (approach section) velocity was increased from 20 to 47 feet per second.

2. Absolute values of the incipient-cavitation parameter indicated local minimum wall pressures less than the vapor pressure corresponding to the liquid temperature. The maximum pressure decrement (effective liquid tension) occurred at 80° F and ranged from 9 feet of liquid Freon-114 at a free-stream (approach section) velocity of 20 feet per second to 20 feet of liquid at 47 feet per second. At 0° F these pressure decrements were about halved.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 3, 1964.

APPENDIX - SYMBOLS

C_p	noncavitating pressure coefficient, $(h_x - h_0)/(V_0^2/2g)$
$C_{p,min}$	noncavitating minimum-pressure coefficient, $(h_{min} - h_0)/(V_0^2/2g)$
D	free-stream (approach section) diameter, 1.743 in. for cavitation model, 8.03 in. for aerodynamic model
g	acceleration due to gravity, 32.2 ft/sec^2
h_{min}	minimum static pressure, ft of liquid Freon-114 abs
h_v	vapor pressure corresponding to free-stream liquid temperature, ft of liquid Freon-114 abs
h_x	static pressure at x/D, ft of liquid Freon-114 abs
h_0	free-stream static pressure at x/D of 1.98 (approach section), ft of liquid Freon-114 abs
K_i	incipient-cavitation parameter, $\left[(h_0 - h_v)/(V_0^2/2g)\right]_{incipient}$
V_0	free-stream velocity at x/D of 1.98 (approach section), ft/sec
x	axial distance from test-section inlet, in. (see fig. 1)

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